DESIGN CONSIDERATIONS AND PERFORMANCE OF MOTOROLA TEMPERATURE-COMPENSATED ZENER (REFERENCE) DIODES

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INTRODUCTION

This application note defines Motorola temperature-compensated zener (reference) diodes, explains the device characteristics, describes electrical testing, and discusses the advanced concepts of device reliability and quality assurance. It is a valuable aid to those who contemplate designing circuits requiring the use of these devices.

Zener diodes fall into three general classifications: Regulator diodes, reference diodes and transient voltage suppressors. Regulator diodes are normally employed in power supplies where a nearly constant dc output voltage is required despite relatively large changes in input voltage or load resistance. Such devices are available with a wide range of voltage and power ratings, making them suitable for a wide variety of electronic equipments.

Regulator diodes, however, have one limitation: They are temperature-sensitive. Therefore, in applications in which the output voltage must remain within narrow limits during input-voltage, load-current, and temperature changes, a temperature-compensated regulator diode, called a reference diode, is required.

The reference diode is made possible by taking advantage of the differing thermal characteristics of forward- and reverse-biased silicon p-n junctions. A forward-biased junction has a negative temperature coefficient of approximately 2 mV/°C, while reverse-biased junctions have positive temperature coefficients ranging from about 2 mV/°C at 5.5 V to 6 mV/°C at 10 V. Therefore it is possible, by judicious combination of forward- and reverse-biased junctions, to fabricate a device with a very low overall temperature coefficient (Figure 1).

The principle of temperature compensation is further illustrated in Figure 2, which shows the voltage-current characteristics at two temperature points (25 and 100°C) for both a forward- and a reverse-biased junction. The diagram shows that, at the specified test current (I_{ZT}), the absolute value of voltage change (ΔV) for the temperature change between 25 and 100°C is the same for both junctions. Therefore, the total voltage across the combination of these two junctions is also the same at these temperature points, since one ΔV is negative and the other is positive. However, the rate of voltage change with temperature over the temperature range defined by these points is not necessarily the same for both junctions, thus the temperature compensation may not be linear over the entire range.

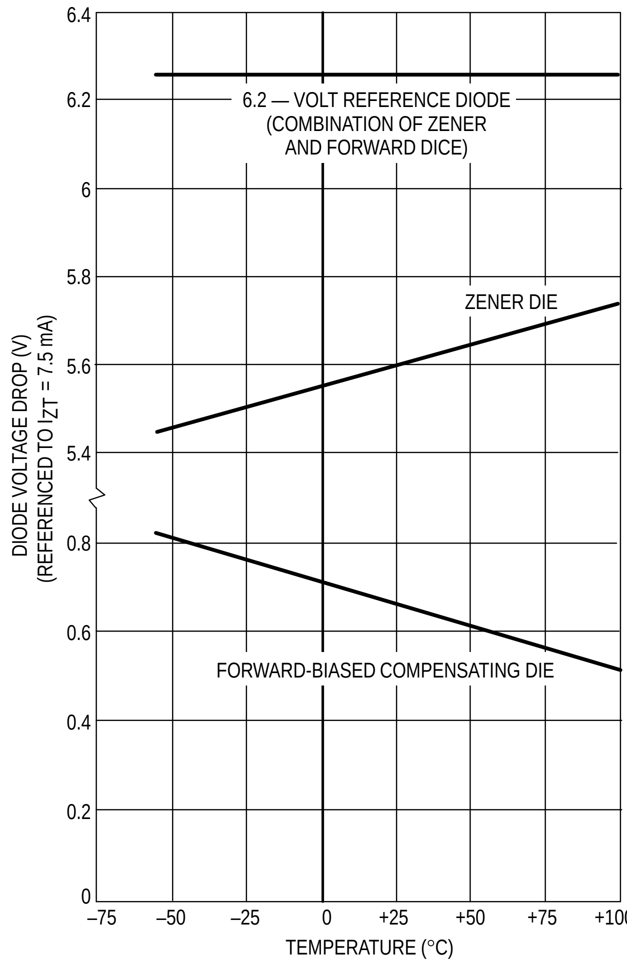


Figure 1. Temperature Compensation of a 6.2 Volt Reference Diode (1N821 Series)

Figure 2 also indicates that the voltage changes of the two junctions are equal and opposite only at the specified test current. For any other value of current, the temperature compensation may not be complete.

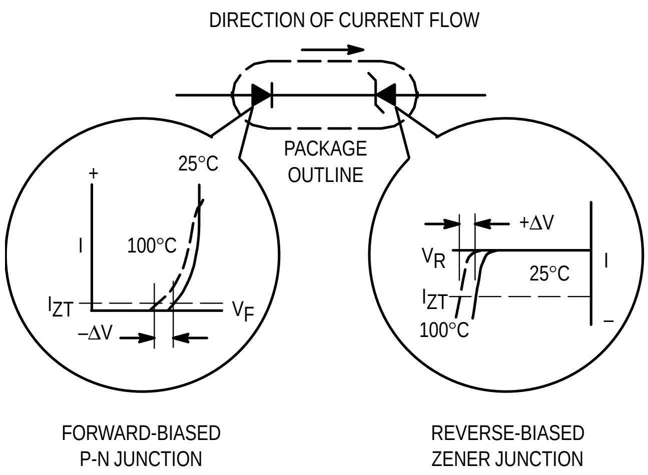


Figure 2. Temperature Compensation of P-N Junctions

IMPORTANT ELECTRICAL CHARACTERISTICS OF REFERENCE DIODES

The three most important characteristics of reference diodes are 1) reference voltage, 2) voltage-temperature stability, and 3) voltage-time stability.

1. Reference Voltage. This characteristic is defined as the voltage drop measured across the diode when the specified test current passes through it in the zener direction. It is also called the zener voltage (V_Z, Figure 3). On the data sheets, the reference voltage is given as a nominal voltage for each family of reference diodes.

The nominal voltages are normally specified to a tolerance of ±5%, but devices with tighter tolerances, such as ±2% and ±1%, are available on special order.

2. Voltage-Temperature Stability. The temperature stability of zener voltage is sometimes expressed by means of the temperature coefficient. This parameter is usually defined as the percent voltage change across the device per degree centigrade. This method of indicating voltage stability accurately reflects the voltage deviation at the test temperature extremes but not necessarily at other points within the specified temperature range. This fact is due to variations in the rate of voltage change with temperature for the forward- and reverse-biased dice of the reference diode. Therefore, the temperature coefficient is given in Motorola data sheets only as a quick reference, for designers who are accustomed to this method of specification.

A more meaningful way of defining temperature stability is the "box method." This method, used by Motorola, guarantees that the zener voltage will not vary by more than a specified amount over a specified temperature range at the indicated test current, as verified by tests at several temperatures within this range.

Some devices are accurately compensated over a wide temperature range (–55°C to 100°C), others over a narrower range (0 to 75°C). The wide-range devices are, as a rule, more expensive. Therefore, it would be economically wasteful for the designer to specify devices with a temperature range much wider than actually required for the specific device application.

During actual production of reference diodes, it is difficult to predict the compensation accuracy. In the interest of maximum economy, it is common practice to test all devices coming off the production line, and to divide the production lot into groups, each with a specified maximum ΔV_Z. Each group, then, is given a different device type number.

On the data sheet, the voltage-temperature characteristics of the most widely used device types are illustrated in a graph similar to the one shown in Figure 4. The particular production line represented in this figure produces 6.2 volt devices, but the line yields five different device type numbers

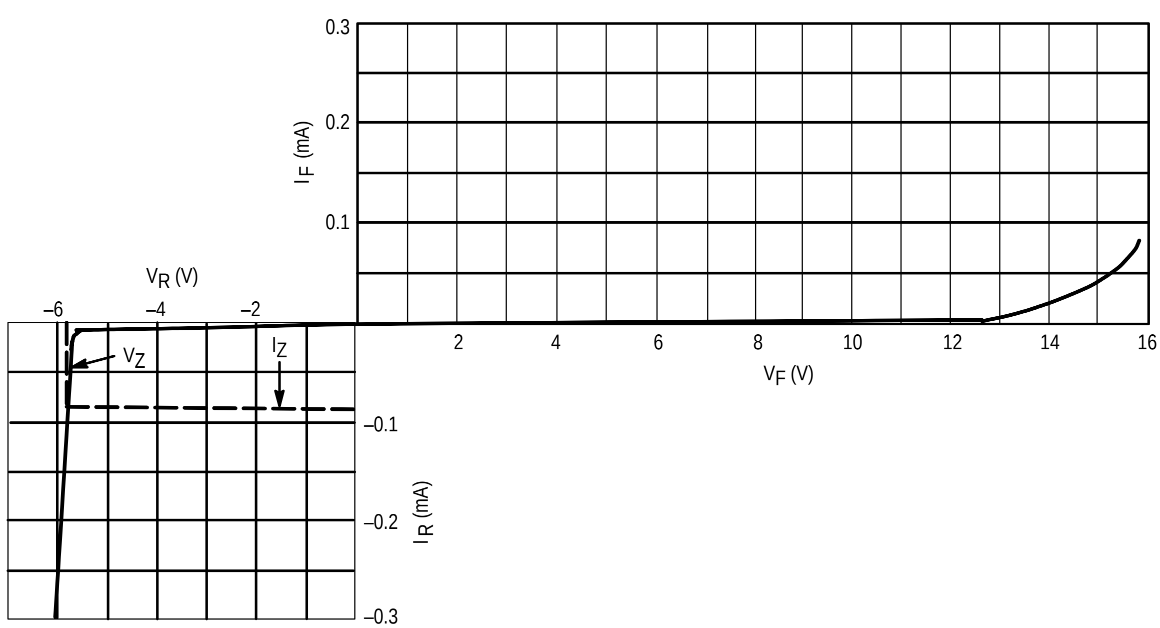
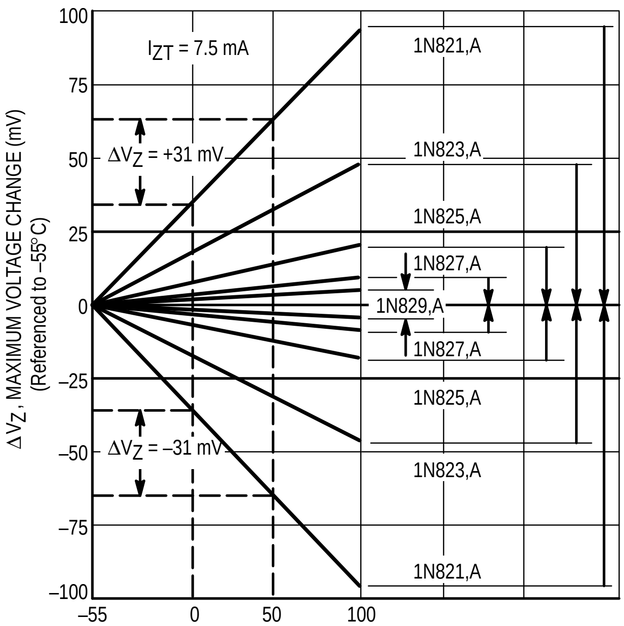


Figure 3. Typical Voltage — Current Characteristic of Reference Diodes

(1N821 through 1N829), each with a different temperature coefficient. The 1N829, for example, has a maximum voltage change of less than 5 mV over a temperature range of –55 to +100°C, while the 1N821 may have a voltage change of up to 96 mV over the same temperature range.



In the past, design data and characteristic curves on data sheets for reference diodes have been somewhat limited: The devices have been characterized principally at the recommended operating point. Motorola has introduced a data sheet, providing device data previously not available, and showing limit curves that permit worst-case circuit design without the need for associated tests required in conjunction with the conventional data sheets.

Figure 4. Temperature Dependence of Zener Voltage (1N821 Series)

Graphs such as these permit the selection of the lowest-cost device that meets a particular requirement. They also permit the designer to determine the maximum voltage change of a particular reference diode for a relatively small change in temperature. This is done by drawing vertical lines from the desired temperature points at the abscissa of the graph to intersect with each the positive- and negative-going curves of the particular device of interest. Horizontal lines are then drawn from these intersects to the ordinate of the graph. The difference between the intersections of these horizontal lines with the ordinate yields the maximum voltage change over the temperature increment. For example, for the 1N821, a change in ambient temperature from 0 to 50°C results in a voltage change of no more than about ±31 mV.

The reason that the device reference voltage may change in either the negative or positive direction is that after assembly, some of the devices within a lot may be overcompensated while others may be undercompensated. In any design, the "worst-case" condition must be considered. Therefore, in the above example, it can be assumed that the maximum voltage change will not exceed 31 mV.

It should be understood, however, that the above calculations give the maximum possible voltage change for the device type, and by no means the actual voltage change for the individual unit.

3. Voltage-Time Stability. The voltage-time stability of a reference diode is defined by the voltage change during operating time at the standard test current (I_{ZT}) and test temperature (T_A). In general, the voltage stability of a reference diode is better than 100 ppm per 1000 hours of operation.

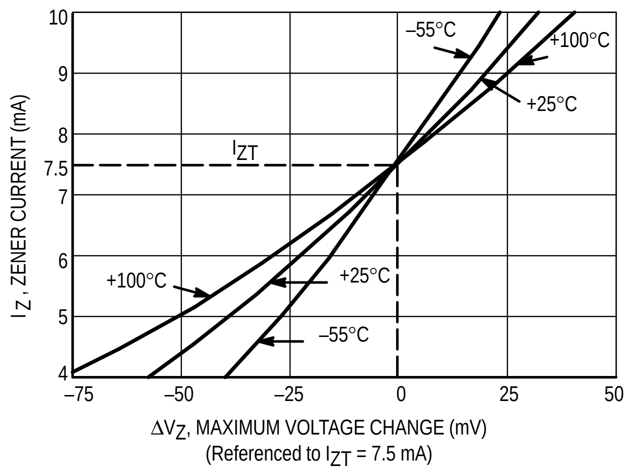


Figure 5. Current Dependence of Zener Voltage at Various Temperatures (1N821 Series)

THE EFFECT OF CURRENT VARIATION ON ZENER VOLTAGE

The nominal zener voltage of a reference diode is specified at a particular value of current, called the zener test current (I_{ZT}). All measurements of voltage change with temperature are referenced to this test current. If the operating current is varied, all these specifications will change.

The effect of current variation on zener voltage, at various temperatures, is graphically illustrated on the 1N821 data sheet as "Zener Current versus Maximum Voltage Change." A typical example of such a graph is shown for the 1N821 series in Figure 5. The voltage change shown is due entirely to the impedance of the device at the fixed temperature. It does not reflect the change in reference voltage due to the change in temperature since each curve is referenced to I_{ZT} = 7.5 mA at the indicated temperature. As shown, the greatest voltage change occurs at the highest temperature represented in the diagram. (See "Dynamic Impedance" under the next section).

Figure 5 shows that, at 25°C, a change in zener current from 4 to 10 mA causes a voltage shift of about 90 mV. Comparing this value with the voltage-change example in Figure 4 (31 mV), it is apparent that, in general, a greater voltage variation may be due to current fluctuations than to temperature change. Therefore, good current regulation of the source should be a major consideration when using reference diodes in critical applications.

It is not essential, however, that a reference diode be operated at the specified test current. The new voltage-temperature characteristics for a change in current can be obtained by superimposing the data of Figure 5 on that of Figure 4. A new set of characteristics, at a test current of 4 mA, is shown for the 1N823 in Figure 6, together with the original characteristics at 7.5 mA.

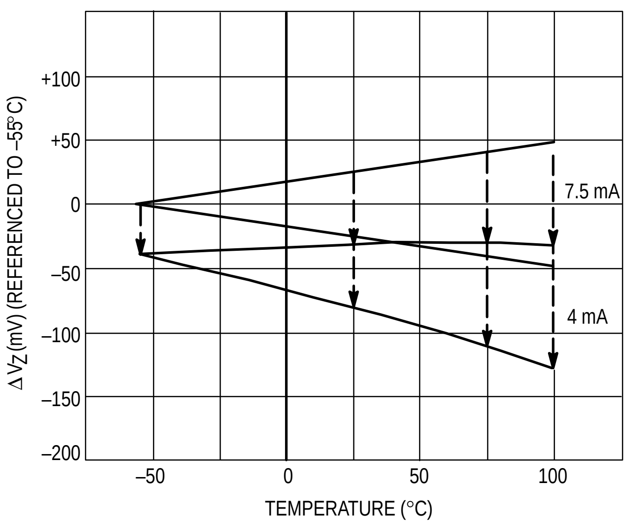


Figure 6. Voltage Change with Temperature for 1N823 at Two Different Current Levels

From these characteristics, it is evident that the voltage change with temperature for the new curves is different from that for the original ones. It is also apparent that if the test current varies between 7.5 and 4 mA, the voltage changes would lie along the dashed lines belonging to the given temperature points. This clearly shows the need for a well-regulated current source.

It should be noted, however, that even when a well-regulated current supply is available, other factors might influence the current flowing through a reference diode. For example, to minimize the effects of temperature-sensitive passive elements in the load circuit on current regulation, it is desirable that the load in parallel with the reference diode have an impedance much higher than the dynamic impedance of the reference diode.

OTHER CHARACTERISTICS

In addition to the three major characteristics discussed earlier, the following parameters and ratings of reference diodes may be considered in some applications.

Power Dissipation

The maximum dc power dissipation indicates the power level which, if exceeded, may result in the destruction of the device. Normally a device will be operated near the specified test current for which the data-sheet specifications are applicable. This test current is usually much below the current level associated with the maximum power dissipation.

Dynamic Impedance

Zener impedance may be construed as composed of a current-dependent resistance shunted by a voltage-dependent capacitance. Figure 7 indicates the typical variations of dynamic zener impedance (Z_Z) with current and temperature for the 1N821 reference diode series. These diagrams are given in the 1N821 data sheet. As shown, the zener impedance decreases with current but increases with ambient temperature.

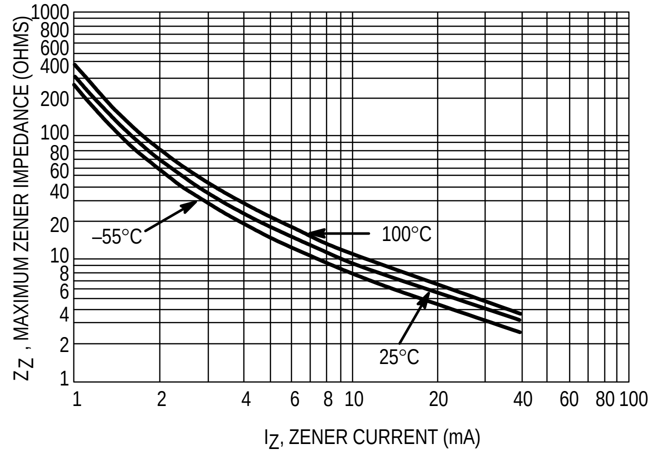


Figure 7. Variation of Zener Impedance With Current and Temperature (1N821 Series)

The impedance of a reference diode is normally specified at the test current (I_{ZT}). It is determined by measuring the ac voltage drop across the device when a 60 Hz ac current with an rms value equal to 10% of the dc zener current is superimposed on the zener current (I_{ZT}). Figure 8 shows the block diagram of a circuit used for testing zener impedance.

ELECTRICAL TESTING

All devices are tested electrically as a last step in the manufacturing process.

The subsequent final test procedures represent an automated and accurate method of electrically classifying reference diodes. First, an electrical test is performed on all devices to insure the correct voltage-breakdown and stability characteristics. Next, the breakdown voltage and dynamic impedance are measured. Finally, the devices are placed in an automatic data acquisition system that automatically cycles them through the complete temperature range specified. The actual voltage measurements at the various temperature points are retained in the system computer memory until completion of the full temperature excursion. The computer then calculates the changes in voltage for each device at each test temperature and classifies all units on test into the proper category. The system provides a printed readout for every device, including the voltage changes to five digits during temperature cycling, and the corresponding EIA type number, as well as the data referring to test conditions such as device position, lot number, and date.

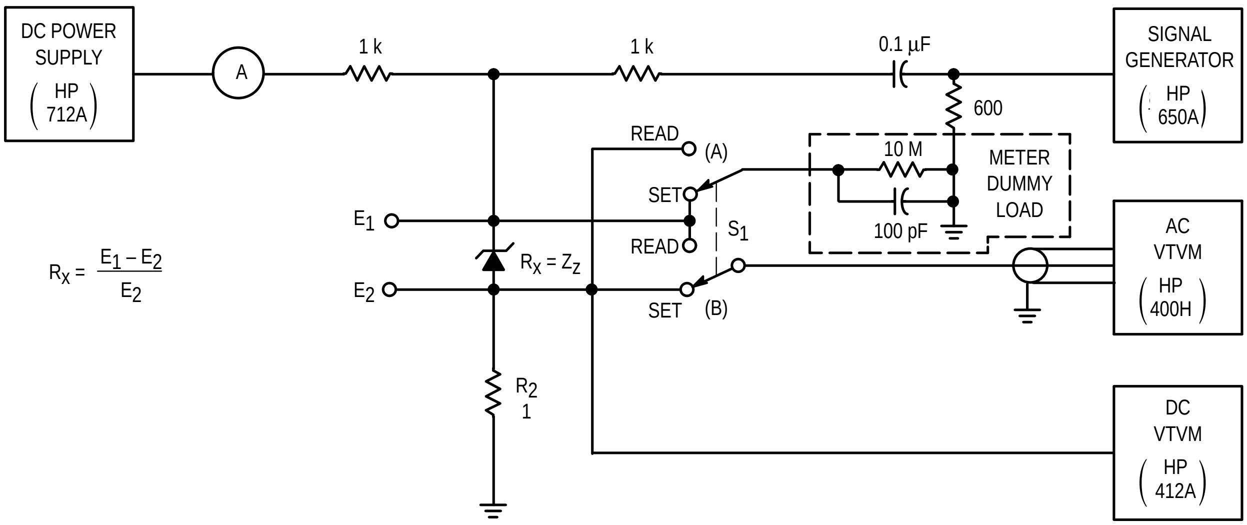


Figure 8. Block Diagram of Test Circuit for Measuring Dynamic Zener Impedance

DEVICE RELIABILITY AND QUALITY ASSURANCE

Insuring a very low failure rate requires maximum performance in all areas effecting device reliability: Device design, manufacturing processes, quality control, and reliability testing. Motorola's basic reliability concept is based on the belief that reference diode reliability is a complex yet controllable function of all these variables.

Under this "total reliability" concept, Motorola can mass-produce high-reliability reference diodes.

The reliability of a reference diode fundamentally depends upon the device design, regardless of the degree of effort put into device screening and circuit designing. Therefore, reliability measures must be incorporated at the device design and process development stages to establish a firm foundation for a comprehensive reliability program. The design is then evaluated by thorough reliability testing, and the results are supplied to the Design Engineering department. This closed-loop feedback procedure provides valuable information necessary to improve important design features such as electrical instability due to surface effects, mechanical strength, and uniformly low thermal resistance between the die and ambient environment.

Process Control

There are more than 2000 variables that must be kept under control to fabricate a reliable reference diode. The in-process quality control group controls most of these variables. It places a strict controls on all aspects of manufacturing from materials procurement to the finished product. Included in this broad spectrum of controls are:

- **Materials Control.** All materials purchased or fabricated in-plant are checked against rigid specifications. A quality check on vendors' products is kept up to date to insure that only materials of a proven quality level will be purchased.
- **In-Process Inspection and Control.** Numerous on-line inspection stations maintain a statistical process control program on specific manufacturing processes. If any of these processes are found to be out of control, the discrepant material is diverted from the normal production flow and the cognizant design engineer notified. Corrective action is initiated to remedy the cause of the discrepancy.

Reliability Testing

The Reliability Engineering group evaluates all new products and gives final conclusions and recommendations to the device design engineer. The Reliability Engineering group also performs independent testing of all products and includes, as part of this testing program, step-stress-to-failure testing to determine the maximum capabilities of the product.